Yale University
School of Forestry
New Haven, Connecticut.

DEVELOPMENT OF NON-DESTRUCTIVE TESTS FOR LAMINATED GUNSTOCK BLANKS.

Progress Report No.1
June 1 to July 31, 1953.

Contract No. SAR/DA-19-059-ORD-1329
Springfield Ordnance District
Department of the Army
Aug. 10, 1953

Development of Non-destructive Tests for Laminated Gunstock Blanks. Progress Report No. 1 for the Period June 1 to July 31, 1953.

Introduction

This is the first of a series of progress reports on work undertaken at the Yale School of Forestry to develop a practical method of testing laminated gunstock blanks. This is to involve a determination of the integrity of the glue bond. The study is sponsored by the Springfield Ordnance District of the Department of the Army under Contract No. SAR/DA-19-059-ORD-1329. Work began on June 1, 1953 with a review of the literature pertaining to this subject.

This report is essentially a summary, compiled from the literature, of the experiments and conclusions of others who have worked in this field, and in addition the results of preliminary experimentation done at Yale. It is intended that this survey of the literature and applicable methods will serve as a guide in the selection of testing techniques to be used in the experimental part of the study. The study anticipates the application of appropriate non-destructive test methods followed by recognized destructive testing of laminated gunstock blanks. These blanks are to be fabricated under production conditions in a commercial laminating plant.

During and since the last war the field of non-destructive testing has greatly expanded to include nearly all types of engineering materials. Its rapid development can be attributed to several factors:

the need for 100 percent testing of certain critical components of an assembly, the dissatisfaction experienced with sampling techniques which occasionally permitted faulty materials to be placed in service, and the large volume of serviceable items rejected as a result of poorly designed inspection methods.

Up to the present time the great bulk of non-destructive testing has been in the field of metals and their alloys. There have been essentially three non-destructive test methods developed; x-ray examination, ultrasonic vibrations, and magnetic particle inspection. In the selection of non-destructive test methods applicable to wood, it is obvious that magnetic particle inspection is impossible due to the non-magnetic character of wood.

Since x-ray absorption and transmission of ultrasonic energy may be applied to all types of engineering materials regardless of their characteristics, these two test methods, therefore, have promise as non-destructive tests for laminated wood.

An extensive search of the literature has been conducted in an effort to uncover any previous application of these two methods to the testing of laminated wood. The following paragraphs present these data as they apply to the non-destructive testing of both wood and laminated wood.

Review of Literature

Testing by x-ray absorption

Makinson (7) reports the use of x-rays in the wood industry in England as applied to laminated wood and plywood to determine bare spots in glue lines. An addition of barium oxide to the glue, which as the author states, "in no way injured it", had the effect of absorbing x-rays.

Bare spots could then be detected immediately by increased penetration of the x-rays at these spots. By means of the same apparatus it was possible to detect knots, inferior cores in plywood and laminated wood, and open joints, as well as hardware such as nails and screws in an assembly. Similarly blistering of spots in glue lines could be detected due to lack of adhesive in these areas.

Maloy and Wilsey (8) report the use of portable x-ray equipment for inspection of shade trees and transmission poles along the city streets in Rochester, N.Y. It was possible to detect insect and fungal damage due to differential absorption of x-rays. They claimed that the wood was responsible for scattering x-rays to such an extent that negatives were not clear and contrasty. To eliminate this effect a Bucky diaphragm was employed. This device consists of a grid of parallel strips of lead moved in front of a film during exposure. Its function is to absorb scattered radiation as well as any secondary radiation emitted by the wood itself. Although the fine structure of the wood could not be determined, it was possible to detect the extent of decay and insect damage by differences in film density. This paper fails to include any detailed description of the equipment used.

Further work of this type has been conducted in Australia by Gregory (2) who reports the use of x-rays for detecting decay, checks, splits, and insect damage in structural timbers. It was possible to differentiate decay from insect damage due to the more clearly defined boundaries of the latter. It was also found advantageous by this investigator to use a Bucky diaphragm to reduce scattering of x-rays. In exposing the films a low power unit operating at 63 kilovolts and 10

milliamperes was used. Gregory concludes that this method of non-destructive analysis of wood could have a definite production application. He also states that x-rays were used in the examination of aircraft timbers during World War 1, but cites no references to substantiate this statement.

Zucker (10) reports the use of portable x-ray equipment for the inspection of transmission poles. By using a Westinghouse Diadex x-ray machine, rated at 85 kilovolts (peak) and 15 milliamperes, it was possible to make radiographs of the poles at the ground line to determine the extent of damage by decay and insects. It was reported that average strengths calculated from radiographs exceeded by only 16 percent actual strengths from bending tests. Calculated strengths were computed by determining the volume of sound wood shown by the radiograph and applying this to a strength formula. For interpretation purposes it was necessary to observe the fiber structure of the wood on the exposed negative. This was necessary, since decayed areas with a high moisture content absorbed more radiation than undecayed wood and thus appeared more sound on the film. Undecayed wood had smooth and precise fiber boundary lines whereas the fiber boundaries of decayed wood appeared stringy or even absent. Analysis of film was, therefore, based on fiber structure with film density as a supplementary indicator.

Kaye (3) reports the use of x-ray equipment for the inspection of wood and wooden aircraft. It was possibly to differentiate the more dense summerwood from springwood, heartwood from sapwood, as well as splits, knots, decayed areas, and checks from the remaining sound wood. It was reported that, since the density of wood is quite low as compared to metals, it was possible to use a very soft x-ray for examination purposes.

As applied to wooden aircraft x-rays were employed in England by Kaye during World War 1 for the inspection of laminated members and aircraft plywood. Detection of low grade material in the inner laminations of glued up members, open edge joints in the inner plies of plywood, and an excess or deficiency of adhesive between members was possible.

Kitazawa (4) reports the use of x-rays for the examination of logs, boards, and laminated timbers. It was possible to detect decay, annual ring alignment, knots, and holes in solid members due to the differential absorption of x-rays. It was reported possible to determine the degree of glue coverage in members laminated with a urea-formaldehyde glue. This was again due to the difference in degree of x-ray absorption of the glue as compared to wood.

For this work a 150 kilovolt x-ray unit was employed. Both radiography and fluoroscopy were used. Both methods had their advantages and disadvantages: radiography produced a permanent, clear record of a member under test, but the time and cost involved in the production was prohibitive; fluoroscopy was a fast, and efficient method of inspection; however, some trouble was experienced with low-screen brightness. Since such a small amount of radiation reaches the screen when viewed fluoroscopically, a very dim image was produced. Kitazawa mentions in the same publication that recent developments in electronics have made it possible to intensify this image on a second screen to produce a brightness of 500 times.

<u>Testing by Ultrasonics</u>

Vibrational waves of a frequency above the hearing range of the normal ear are referred to as ultrasonics. This term,therefore,includes

all frequencies of such waves above 20,000 cycles per second. Ultrasonics have come to have many applications, of which sound ranging, submarine signaling, communications, and materials testing are a few examples. The former three require frequencies in the range of 20,000 to 100,000 cycles per second, while testing materials for flaws requires frequencies in the range of 100,000 to 10,000,000 cycles per second.

Equipment for ultrasonic testing consists essentially of a variable frequency generator, signal amplifier, transducers, and an indicator. The generator is of the radio-frequency type; the transducers may be either a single or a mosaic of quartz crystals, ceramic materials, or the magnetostrictive type. The indicator is usually a cathode ray oscilloscope; however, other devices such as a voltmeter may be used when dealing with certain types of testing.

Testing by ultrasonics is essentially of two different types: (1) through transmission, and (2) the pulse echo method.

Through transmission employs two crystals, one as a sender and one as a receiver. Ultrasonic waves, either pulsed or continuous, introduced into a medium under test, are partially reflected by flaws in the material. The remaining energy of the original wave is transmitted through the material with a reduced amplitude of vibration, thus making it possible to detect a flaw by differences in relative transmission..

The pulse-echo method is designed to send a pulse of ultrasonic energy a few micro-seconds of duration into a medium. Between pulses the transducer acts as a receiver for reflections of the sound energy from the opposite boundary of the medium as well as any internal flaws.

The most thorough and applicable work dealing with the non-destructive testing of wood laminates by ultrasonics was conducted by Galginaitis, Bell, Fine, and Auer (1) at the University of Louisville Institute of Industrial Research.

In dealing with through transmission, these authors tested solid wood, 2-, 3-, and 4-ply laminated blanks, and 2-ply laminated blanks with included glue line defects. These defects took the form of actual glue line voids or small pieces of cellophane which were placed in the glue line to prevent adhesion. Essentially the equipment employed was a variable frequency generator, a quartz crystal transducer (sending), a second quartz crystal transducer for receiving vibrations and converting them to an electrical signal, an amplifier, and an oscilloscope.

The detection of a defective glue line by ultrasonics is dependent on the different accoustic impedences of wood and glue. A portion of the ultrasonic waves striking the boundary of two media of different accoustic impedences will be reflected while a portion will be transmitted to the opposite boundary. It was thought that a defective area in a glue line would prove to be a sufficiently poor impedence match such that most of the energy striking such an area would be reflected rather than transmitted.

In the test set up ultrasonic energy was transmitted through a particular blank, picked up by a quartz crystal transducer on the opposite side and converted to an electric signal, amplified, and viewed on the oscilloscope screen. Sufficient time was allowed for the wave to reach its final value, and then the amplitude of the trace was recorded. By transmission through various areas in a blank a range of values was

obtained, and deviations exceeding those normal to a particular area were detected.

Working with solid wood 2 x 8 x 1/8 in. and 2 x 8 x 1/4 in. these investigators found an average deviation of relative transmissions of various spots along a board of 26 percent, and an average deviation at any one spot of 12 percent at a frequency of 500 kilocycles per second. Blanks of 2-, 3-, and 4-ply laminates, made up of 1/2-in. or 1/4-in. laminations,exhibited an average deviation of relative transmissions at various spots along a board of 43 percent while the average deviation of any one spot was 23 percent. However, it was found that operating at a lower frequency (300 kilocycles per second) considerably reduced the deviations in transmission. Solid wood samples 2 x 8 x 1/8 in. and 2 x 8 x 1/4 in. showed an average deviation of relative transmissions at various spots along a board of 10 percent, and an average deviation of any one spot of 5 percent, while the 2-, 3-, and 4-ply laminates indicated above, exhibited deviations of 19 percent and 6 percent respectively. This seems to indicate that there is a definite variation in the ultrasonic properties of wood, however, this variation is not as pronounced when operating at lower frequencies.

Larger solid wood samples, 8 x 24 in. and varying from 1/8 to 1 in. in thickness exhibited higher transmission values in areas of narrow-growth rings than in areas of wide rings at a frequency of 300 kilocycles per second. It was also found that readings taken near the edges of these boards were not as reproducible as those taken some distance from the edge.

These investigators were able to locate a defective spot in the glue line of a 2-ply laminate with considerable success. In general a

defective area allowed only 1/5 the transmission of adequately bonded areas. A few known defective spots were not located with too much certainty.

Some difficulty was experienced in the selection of a good couplant between transducer and test material. This is of prime importance for an efficient transfer of energy into the medium under test. Several compounds were tried; oils, ethylene glycol, various greases, and a silicone rubber compound known under the trade name of "Bouncing Putty". Of all materials investigated, the silicone rubber compound proved to be the best. Its efficiency was later improved by mixing the putty with "Silastic 123", another silicone rubber compound.

<u>Testing by Audio-frequency methods</u>

Testing at audio-frequencies involves vibrating a specimen at its natural resonant frequency. This frequency is determined by the dimensions, stiffness, mode of vibration, and density of a material and is the frequency at which maximum amplitude of vibration occurs. By the simple relation,

$$c = \sqrt{\frac{E}{d}}$$

where $c =$ velocity of wave propagation

$E =$ Young's modulus

and $d =$ density,

the modulus of elasticity of a material may be determined, and presumably any defects influencing stiffness may be detected.

In research done at the Timber Engineering Company, Kitazawa (5) reports the use of audio-frequency vibration equipment for determining the dynamic modulus of elasticity of small solid wood beams. Two modes of

vibration were used; transverse and longitudinal.

The basic relationship involving sound velocity in wood, modulus of elasticity, and density indicated above, may be transposed to the following equations:

For transverse vibration,

$$f_L = C\sqrt{\frac{gE_L I}{wL^4}}$$

where f_L = natural resonant frequency in c.p.s. for transverse vibration

C = 3.56 for fundamental frequency of beams supported at 0.224L from each end.

g = 386 in/sec^2

E_L = dynamic modulus of elasticity in p.s.i.

I = moment of inertia in in.^{4}

w = weight of unit length beam in lb./in.

L = beam length in inches

For longitdinal vibration,

$$f_{Lc} = \frac{n}{2L}\sqrt{\frac{gE_{Lc}}{d}}$$

where f_{Lc} = natural resonant frequency in c.p.s. for longitudinal vibration

n = 1 for fundamental frequency of beams supported at the midpoint

L = beam length in inches

g = 386 in. /sec ^{2}

E_{Lc} = dynamic modulus of elasticity in p.s.i.

d = density in lb./in.^{3}

In a test of this type, the transverse beam (2 x 2 x 30 in.) is supported at two points 0.224 L in. from either end over the mechanical vibrator. The variable-frequency generator provides an alternating current which is amplified to drive the vibrator and the frequency is increased until the beam is set into vibration. A crystal pick up positioned at the center of the beam converts the mechanical vibrations to an electrical signal. The signal is amplified and projected on the screen of an oscilloscope. Maximum wave amplitude on the oscilloscope screen indicates maximum amplitude of vibration and is associated with the resonant frequency of the piece under test. Having determined the resonant frequency, it is possible to compute the dynamic modulus of elasticity from the preceding formula. Longitudinal vibrational testing was conducted in much the same manner except that the beams were placed on end on the exciter and supported at the midpoint.

It was found that the dynamic modulus of elasticity in transverse vibration averaged about 10 percent higher than the modulus derived from static bending tests. No comparison of static and dynamic longitudinal moduli was made. Although this non-destructive test method cannot be applied to the location of defects, it nevertheless does have an application in the evaluation of the stiffness of a solid wood or possibly a laminated wood blank.

In a succeeding article of the same nature, Kitazawa (6) reports much the same results in the dynamic transverse testing of smaller beams (2 x 2 x 30 cm). In addition data on the influence of moisture content and grain angle on the dynamic modulus of elasticity were also presented.

Non-destructive testing of laminated wood in the audio-frequency range of sound, in addition to that done in the ultrasonic range, was also conducted at the University of Louisville by Galginaitis, and associates (1).

In this work a specimen was vibrated longitudinally at its natural resonant frequency. This vibratory motion was picked up by a quartz crystal or other appropriate mechanism that converted it to an electrical signal, and the amplitude of vibration was observed on an oscilloscope screen. When a vibrating specimen is allowed to come to rest the amplitude of vibration rapidly falls to zero. This decay of vibration was observed on the oscilloscope screen, photographed, and correlated with a destructive test of the sample.

For this work two types of transducers were employed: a condenser type consisting of two metallic plates separated by a dielectric material and a moving coil or loudspeaker type. Two types of detectors were also used; a crystal and a variable reluctance type. Other equipment was essentially the same as that described in the through transmission of ultrasonic energy.

The results of this experimentation were not as encouraging as those previously described with ultrasonics. The resonant frequency of laminated specimens free from glue line defects did not appear to differ at all consistently after the specimens had been sheared along a glue line and re-assembled to deliberately produce a defective glue line. Similarly the decay of vibration pattern of specimens exhibited no consistent trend after the specimens had been sheared along a glue line and re-assembled to deliberately produce a defective glue line.

It was stated that the failure of the experiments to show any definite trends indicated a need for refinement of the equipment.

H. O. Williams (9) of the Douglas Aircraft Company reports an interesting method for determining unbonded areas in honeycomb sandwich panels. The method involved the use of a variable frequency generator attached to an audio-frequency oscillator which was installed at the small end of a trumpet. The bonded honeycomb panels to be tested were placed over the trumpet. Sand of small grain size was spread over the surface of the panel and the pitch of the audio oscillator varied until the sand began to jump. In vibrating the sand moved away from the unbonded areas which were vibrating more violently than the bonded areas in the glue line. The oscillator used for this inspection had a frequency range of 16 to 30,000 cycles per second. In the course of the tests a frequency of 20,000 cycles per second was found to be most satisfactory.

Experimental Testing

Testing by x-ray absorption

Two blanks (2 x 2 x 12 in.), each consisting of two 1 x 2 x 12-in. laminations have been fabricated with a phenol-formaldehyde adhesive (Cascophen LT-67). The adhesive used in one blank was mixed according to the manufacturers specifications. The adhesive of the second blank, however, included 15 percent by weight of barium sulfate.

Both blanks were laminated with American Beech (*Fagus grandifolia*) and assembled in a manner to deliberately produce glue line defects. These defects took the form of an area completely devoid of adhesive, an area containing a small piece of cellophane, and a heavily waxed area. It was thought that areas of these types should prevent the development of adequate bonds.

The blank assembled with pure adhesive was x-rayed with the plane of the glue line normal to the x-ray beam. Exposures were made at 60 milliamperes for .7 second at kilovoltages of 30, 40, 50, and 60. Observations of the exposed negatives showed that an exposure of 30 to 35 kilovolts, with milliamperage and exposure time approximately the same as indicated above, would produce optimum negative density when x-raying two inches of wood thickness.

Additional exposures were made with the blank assembled with the pure adhesive as well as with the blank with barium sulfate in the glue line at 60 milliamperes, .7 to .9 second of exposure, and kilovoltages ranging from 30 to 35. The void area in the glue line containing barium sulfate was detectable when the plane of the glue line was normal to the

x-ray beam. When the blank was inclined so that the projection of the plane of the glue line on the negative was approximately 1/8 to 1/4 its actual width, the void became even more prominent. The void in the blank assembled with pure adhesive as well as other defective areas in both blanks could not be detected with any degree of certainty, whether the glue line was normal or inclined to the x-ray beam. The void area in the blank assembled with the adhesive containing barium sulfate is shown in Fig. 1, photographed without magnification. The dark strip in the middle of the blank represents the projection of the obliquely placed glue line on the negative. The light spot at the left edge is the void.

For detection of areas devoid of adhesive, x-ray absorption appears to have a definite application; however, it does not seem possible to detect areas containing adequate adhesive, but in which no bonding has occurred.

Testing by ultrasonics

Some preliminary investigations have been made on the transmission of ultrasonic energy through the same laminated blanks described in the section on x-ray testing.

Small blocks of barium titanate ($BaTiO_3$), a ceramic type material, have been assembled into two transducers and continuous through transmission of ultrasonic energy through the laminates has been tried. These blocks resonate at 140 kilocycles per second. However, they can be driven efficiently at harmonics, thus making it possible to test at more than one frequency with the same transducer.

Equipment used for the transmission of ultrasonic energy con-

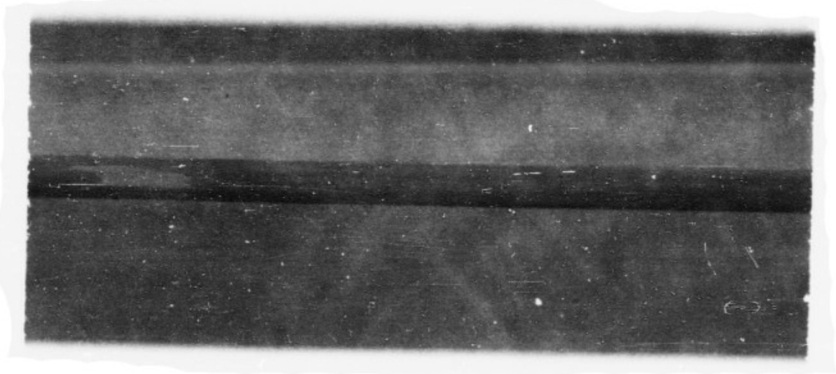

Fig. 1. X-ray of a 2-ply laminated blank with a glue line void at the left edge. The blank has been inclined so that the projection of the glue line on the negative is approximately 1/4 its actual width. This projection is represented by the dark strip in the center of the blank.

sisted of a variable frequency generator, an amplifier, the transducers described above, and an oscilloscope. This equipment was used in the laboratory of the Electrical Engineering School, Yale University.

Of several couplants that have been tried in this study including sponge rubber, sheet cork, oils, glycerol, inner-tube rubber, and "Bouncing Putty" (a silicone rubber compound), the latter was found to be the most efficient in the transfer of ultrasonic energy from the transducer to the laminates under test.

A few ultrasonic transmissions through both blanks have not resulted in any consistent transmission values or the definite location of void or unbonded areas. This has been attributed to several factors: need for refinement of equipment for holding and applying pressure to the transducers, need for a better couplant that will not flow under pressure, and need for adequate electrical shielding of component parts of the test apparatus to prevent pick up of extraneous signals.

Plans for the immediate future call for the fabrication of a limited number of laminated walnut blanks patterned after the construction used in gunstock types B and C, Class 1. These will be assembled in our own laboratory according to the specifications outlined in the final report by Gamble Brothers, Louisville, Kentucky, on Laminated Gunstock Blanks, Research No. G.G. 3728, Order No. S.A. 7220-50, March 14, 1952. However, these blanks will purposely include glue line defects in the form of void areas as well as areas containing adequate adhesive but in which no bonding has occurred. Half of these will be glued with pure adhesive and half with the barium sulfate modification described previously. The

blanks will then be x-rayed at various angles to determine the optimum angle for detection of voids in the principal glue lines as well as the edge joints. After refinement of the testing technique these same blanks will be tested by through transmission of ultrasonic energy.

Results of these preliminary tests will serve as a basis for the selection of methods to be employed subsequently in the testing of commercially fabricated gunstock blanks.

By: Ben A. Jayne

Ben A. Jayne
Technical Assistant

Approved by: Frederick F. Wangaard

Frederick F. Wangaard
Research Supervisor

Literature Cited

1. Galginaitis, S.V., E.R.Bell, A.M.Fine, and G. Auer. The Non-destructive Testing of Wood Laminates. Tech. Rept. No. 1. Office of Naval Research, University of Louisville Institute of Industrial Research. January 1953.

2. Gregory, J.N. X-rays and Timber Defects. Jour. Coun. Sci. and Ind. Res. Div. of For. Prod. Report 80. Australia 13(4): 310-312. 1940.

3. Kaye, G.W.C. The Practical Application of X-rays. E.P.Dutton and Co. New York. 1923.

4. Kitazawa, George. Non-destructive Testing of Wood by X-rays. Southern Lumberman, 179 (2249): 170-171. December 15, 1949.

5. ------------------ Non-destructive Testing for Forest Products. Proceedings Forest Products Research Society, 4:191-197. June 1950.

6. ------------------ Young's Modulus of Elasticity of Small Wood Beams by Dynamic Measurements. Journal Forest Products Research Society 2(5): 228-231. December 1952.

7. Makinson, J.T. X-rays in the Wood Industry. Wood (London) 2(5):215. May 1937.

8. Maloy,T.P., and R.B.Wilsey. X-raying Trees. American Forests and Forest Life, 36(2): 79-82. February 1930.

9. Williams, H.O. Sonic Tester Checks Bonding of Honeycomb Panels. American Machinist, 96(18): 116-117, September 15, 1952.

10. Zucker, M. X-ray Inspection, a New Engineering Tool. Electrical World, 113(12): 33-35. March 23, 1940.

Distribution List

Commanding Officer
Springfield Armory (4)
Springfield 1, Massachusetts

Office of the Chief of Ordnance
Department of the Army (1)
Washington 25, D. C.

Attention: ORDTS
District Chief (1)
Springfield Ordnance District
Springfield 1, Massachusetts
Att.: Contracting Officer

Central Air Documents Office
U. B. Building (2)
Dayton 2, Ohio